Chapter 5 Approach

Recognizing that wayfinding is a fundamental problem impeding the developmental progress of virtual environments, research should point the way toward a methodology for the design of virtual worlds which facilitate skillful wayfinding behavior. Furthermore, this behavior should be exhibited in both experienced and novice users alike because in many cases, exposure to any one virtual world is limited thus eliminating any chance of significant spatial learning. Such a methodology would be founded on a set of design principles which can be shown to hold for virtual spaces. However, at this time, no such set of principles exists. The objective of this dissertation research is to extend the wayfinding design principles described in the previous two chapters into the virtual world domain.

The approach taken is based on Card, Moran, and Newell's (1983) human information-processor model. As shown in Figure 5-1, human information processing goes through three stages; perception, cognition, and motor. Initially, stimuli are perceived through the senses. In the context of virtual worlds, this typically involves viewing a graphical image on a display device, hearing an acoustic spatially-oriented sound, and possibly feeling tactile or haptic feedback. Note that this level of processing corresponds to what Passini (1984) refers to as sensory information (I_s). This information is then manipulated in some fashion by cognitive processes. In the most trivial case, perceptual information is simply connected to its corresponding motor response. More often, memory, attention, arousal, and other high-level systems come into play. This level encompasses Passini's memory information (I_m), and inferred information (I_i). Decisions are made based on all environmental information as to the motor response to be executed. The motor response is what we perceive externally as behavior.

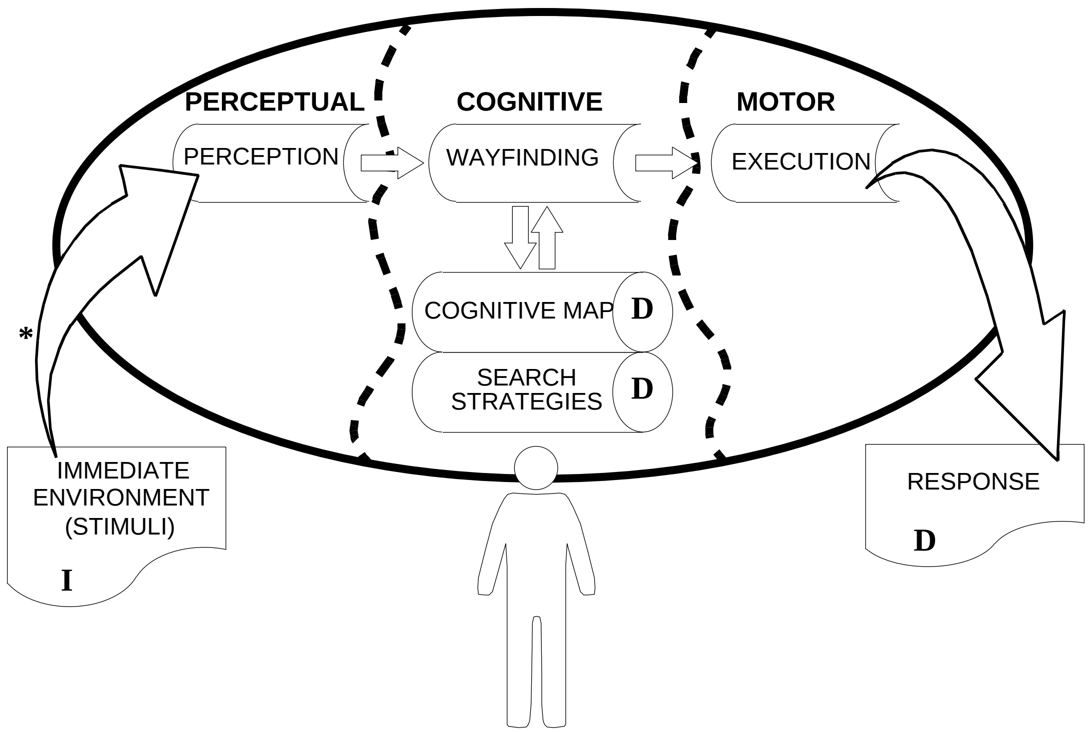

Figure 5-1 A simple information processing model of spatial orientation.

In the case of wayfinding tasks, the stimuli are the immediately surrounding environment. This is the independent variable (Indicated by an **I** in Figure 5-1). Design principles guide the structure of the environment and consequently, the stimuli. In virtual worlds, all stimuli are synthetically generated. Therefore, there is a filtering effect between the stimuli generated by the computer and that which are actually perceived by the user. (See Figure 5-2. The filtering effect is shown as an asterisk in Figure 5-1.) For example, a textual feedback system in a head-mounted display of 300x100 pixel resolution will not be functional. This effect includes many other system parameters besides resolution. Until peripheral devices reach a performance level comparable to human perceptual capabilities, virtual world designers must be aware of their limitations. Although this filtering phenomenon may have an adverse effect on human wayfinding performance, in any virtual environment implementation, it remains constant. Therefore, for the purposes of this experiment, we will also hold it constant in order to study wayfinding principles.

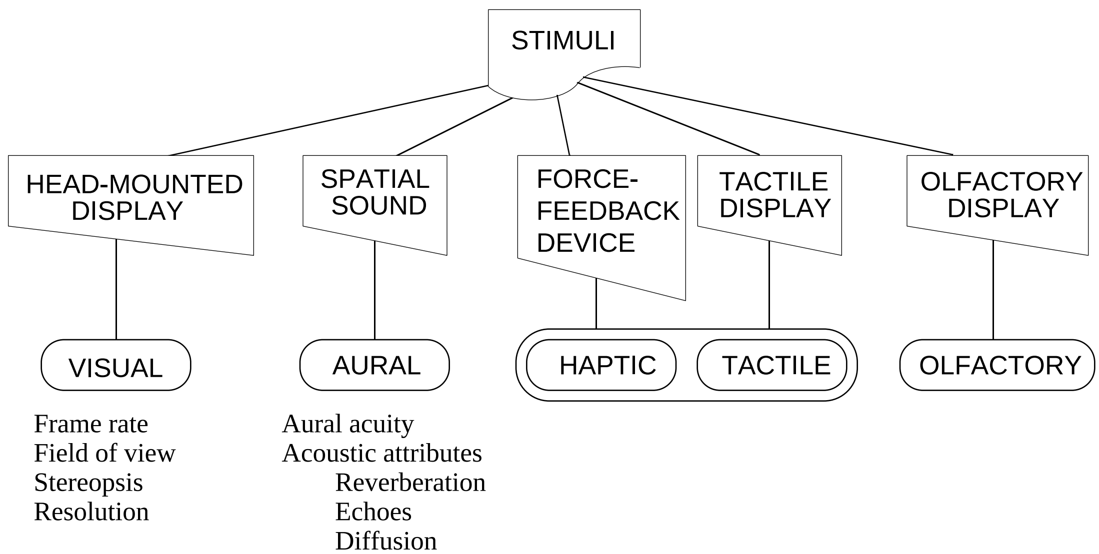

Figure 5-2 The expected versus actual perceived stimuli effect.

The actual cognitive process of wayfinding involves both the subject's cognitive map and search strategies. The cognitive map, as described in Cognitive Map Theory on page 26, is the subject's mental representation of the environment. Search strategies are similar to what Card, Moran, and Newell (1983) describe as *search control knowledge.* As the way-finder gathers experience with a particular environment or type of environment, search strategies are developed which can be used on subsequent searches. For example, a way-finder notices that police departments are most often found on primary streets. A subsequent search for a police department, even in a foreign town, will use this knowledge to constrain the search. It is this knowledge, in part, that Card, Moran, and Newell use to describe *skill* and *skillful behavior* (See Skillful Behavior on page 7). Adapted to wayfinding in virtual worlds, we describe "skillful" in terms of movement actions associated with wayfinding tasks. Skillful wayfinders will exhibit oriented, purposeful movement while novices will become disoriented, executing observable actions to reaquire their orientation.

Notice that skill is expressed through behavior (Card, Moran, & Newell, 1983). This is the response shown in Figure 5-1. It is observable and measurable (Indicated by a **D** in Figure 5-1 as the dependent variables). Through methods such as verbal protocol analysis and map drawing exercises, we can gain insight into the cognitive processes involved with wayfinding and search strategies.

The experiment described in this dissertation is intended to determine what effects, if any, real-world environmental design principles have on the performance of wayfinding tasks in virtual worlds. Before we can do this, however, there are a few items of interest in need of further clarification. First of all, most of the design principles described in the previous chapter are specific to their particular environment. They will have to be generalized as to their objective and purpose rather than their implementation and form. Next, wayfinding tasks have not been defined clearly. The set of wayfinding tasks must be enumerated so that the effects of the design principles can be observed on each of them. Lastly, the term “virtual worlds” is extremely nebulous. Unlike the physical world, few assumptions can be made as to the form, structure, or content of a virtual world. Therefore, the characteristics of space will be structured into a taxonomy. Although the experiment will not attempt to cover all combinations of spaces, tasks, and principles, it will show the validity of these principles to virtual spaces in general. Further, we make no claims that the set of principles described here are the *only* principles which apply to virtual world design; only that these principles do apply and that they effectively improve performance on wayfinding tasks.

Wayfinding Principles

Environmental organization principles are meant to provide the necessary structure by which an observer can mentally organize the environment into a spatial hierarchy capable of supporting wayfinding tasks. The objective is to develop survey knowledge efficiently and accurately (Lynch, 1960) as survey knowledge is the key to skillful wayfinding. Organizational principles intended to achieve this goal are:

1. Divide the large world into distinct small parts, preserving a sense of “place”. This should be hierarchical in nature.
2. Organize the small parts under a simple organizational principle.

Furthermore, the wayfinder must always be properly oriented with the space. If disoriented, new spatial knowledge may be encoded erroneously and existing spatial knowledge may be difficult or impossible to apply to wayfinding problems. Therefore, a third principle is included:

3. Provide frequent directional cues.

The importance of maps to spatial knowledge acquisition cannot be overlooked. Ideally, this knowledge should be flexible, as if the observer had obtained it directly from experience. However, as noted earlier, navigators of virtual worlds are often not given enough exposure to any one world to develop this form of knowledge. Therefore, map design principles are intended to present spatial information in such a way as to produce a flexible, orientation-independent representation of the environment.

1. Show organizational elements (paths, landmarks, districts, etc.) and particularly the organizational principle.
2. Always show the observer’s position.
3. Orient the map with respect to the observer such that the forward-up equivalence principle is accommodated.

These are the principles which will be verified for use in virtual worlds in the experiment described in the next chapter. They maintain the essence of purpose in the principles described by Lynch and Passini without being specific as to implementation. For this reason, the use of signs has been purposely excluded as it is a specific form of the general principles described here. Although it could be argued that the same could be said about maps, their significance in the areas of spatial knowledge acquisition and representation in the experimental psychology literature and their direct application to the goals of this research warrant their investigation.

Wayfinding Tasks

Although there are infinitely many spatial tasks a virtual world operator may wish to perform, we are primarily concerned only with those that involve physical movement from one location to another. In order to consider all tasks, we ask the simple question, “When you move, why are you moving?”. Assuming that only task-related, purposeful movement takes place (i.e. We don’t consider the case of virtual jogging.), there are two broad classifications of possible tasks: searching and exploring. Searching is goal-directed movement while exploration is searching without a goal. More specifically, wayfinding tasks can be classified into three primary categories:

1. ***Naive search*:** Any searching task in which the navigator has no a priori knowledge of the whereabouts of the target in question. A naive search implies that an exhaustive search is to be performed.
2. ***Primed search*:** Any searching task in which the navigator has some prior knowledge of the location of the target. This knowledge could be anything from having seen it previously to some knowledge of where it is not. In any case, the search is non-exhaustive.
3. ***Exploration*:** Any other wayfinding task in which there is no target.

The three types of wayfinding tasks are mutually exclusive. If movement cannot be classified as a search, then it is exploration. Likewise, if a search cannot be classified as a naive search, then it must be primed. However, a high-level wayfinding task may be hierarchical in nature. In other words, a primed search may be used to locate a particular general place but a naive search must then be used within that place to locate the target. The opposite ordering is equally possible (See Figure 5-3). Notice that the classification of the type of search has to do with its nature at any instant in time during execution. Any searching task, however complex, can be broken down into these two fundamental components.

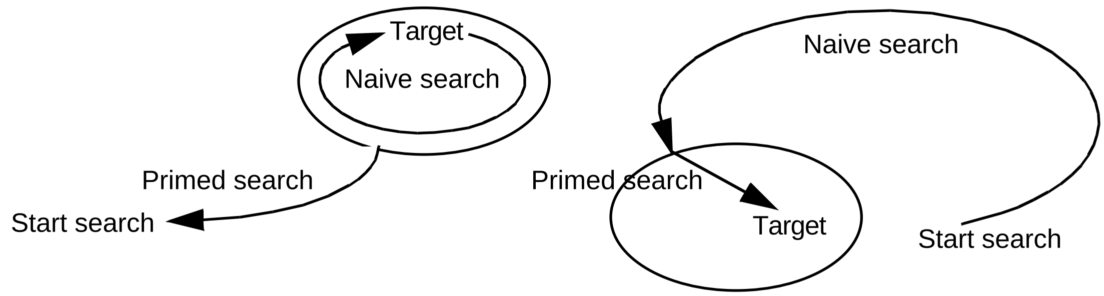

Figure 5-3 The hierarchical nature of compound wayfinding tasks.

Certainly, purely naive searches with no primed element are rare in the real world. However, in virtual worlds, complete spatial naivete is common in first-time explorers of a space; even by the world builder. A scientist may be visualizing data sets computed off-line. These are loaded into some standard format and visualized in a virtual world. Even the scientist may have no idea what to expect. Therefore, support for naive searching must be a part of virtual world design methodology.

We cannot overlook or underestimate the influence of experience and expectation on wayfinding tasks. The reason that purely naive searches are rare in the real world is that it is nearly impossible to describe a situation in which the searcher has absolutely no a priori knowledge with which to guide a search. This knowledge may be the result of experience, cultural or social expectation, or possibly intuition or some other strategy.

In addition to (and often in support of) a priori knowledge, certain cues remain constant and are always available. The rising and setting sun, gravity, and the spherical topology of the Earth are among these. All of these factors serve to effectively eliminate the pure naive search from the domain of wayfinding in the real world.

Typically, wayfinding tasks are not primary tasks but are only one component of a higher level task. For example, the task of moving an object from location A to location B involves a search for both A and B.

Linking wayfinding tasks to spatial knowledge, we find that each type of task is best served by well developed survey knowledge (Lynch, 1960). An optimal naive search demands an exhaustive search of the entire space (in the worst case) once. An exhaustive search is difficult if not impossible to perform if the navigator cannot discern one place from another in order to logically cover the space as a whole. To facilitate naive searches, there must be a method of organizing the space to eliminate multiple passes or skipping entire areas. A primed search, on the other hand, can be performed with only simple procedural knowledge but often results in non-optimal paths. If movement is unrestricted (as it often is in virtual worlds), the navigator need only know the direction and distance to the target location. Minimal configurational knowledge is required relating the navigator's present position to the target's position. Survey knowledge provides the necessary information to find short-cuts through parts of the world the navigator may have never explored in order to reach the target destination. Lastly, exploration is a task intended to develop survey knowledge. A world which does not supply cues to facilitate topological knowledge elicitation cannot support an accurate mental representation.

At this point, we have concluded that *optimal performance on all forms of wayfinding tasks is directly related to the depth of survey knowledge the navigator may have concerning the space*.

Spatial Characteristics

A virtual world designer has control over much more than the basic elements of design outlined by Lynch and Passini in the previous chapter. In fact, virtual world designers control all aspects of space as it is the space itself which is being built, not merely specific attributes of the contents of the space. This brings up an important point. What are the characteristics of space that the virtual world designer can control? The following is a taxonomy of spatial characteristics. The characteristics are enumerated in Table 5-1.

Extent

The extent characteristic refers to the visual extent of the space. In other words, how much space is there? The extent of a space can be discrete or infinite. A discrete space has a definite boundary while an infinite space does not. A classification of infinite typically

Characteristic	Possibilities	Examples
Extent	Close/Discrete Far/ Infinite	A simple room A planet
Detail	Indistinct Intelligible Confounding	A 3D scatter plot A home interior Times square
Density	Sparse Dense	A Naval exercise A shopping mall
Scale	Small Large	The virtual windtunnel A city (Assume 1:1 human scale)
Dimension	Planar Volumetric	A walkthrough (2D) A flythrough (3D)
Distribution	Uniform Clustered	An architectural walkthrough A Naval battle group simulation
Activity	Static Dynamic	A building City streets
Accessibility	Restricted Free	Building corridors An open field
Occlusion	Obstructed Clear	A building Open sea
Organization	Amorphous Structured Schematized	A 3D scatter plot A house Manhattan

Table 5-1 A classification system for spatial characteristics.

implies some infinite topological shape such as spherical or toroidal. However, in terms of virtual worlds, the extents of a space can be mathematically defined as infinite without such a shape.

The classification of close versus far extent is largely subjective and application-specific. This ambiguity will be addressed in Density on page 92. Extent is basically a continuum spanning all spaces from an infinitesimal volume to an infinitely immense space. Note that an infinite space must be of far extent. Also, a classification of close extent implies a discrete space. However, the reverse is not necessarily true. A classification of far extent may be an infinite or discrete space. And a discrete space may be of close or far extent.

Detail

The type of detail present can be indistinct on one end of the spectrum, where all stimuli are so identical, they cannot be distinguished from each other, or confounding on the other end of the spectrum, where all stimuli are different. Somewhere in the middle is the average space which doesn’t go to either extreme; an intelligible space. This is directly related to what Lynch refers to as singularity and continuity (See Generalized Environmental Design Principles on page 74.). An environment must have certain cues which are different and distinguishable but also must have continuity of form so the observer can cluster regions together. The labels applied here to the two extremes, indistinct and confounding, have both been shown by Lynch and Passini to contribute to poor design.

Density

Density refers to the spatial density of visual (or other) stimuli. A sparse world would be one in which there were very few perceptible cues. So few, in fact, that the observer’s visual field may often be blank; a complete void. A dense world, alternatively, would be one in which there were very many perceptible cues. The density may be so high that the visual field is constantly occluded (See Occlusion on page 95).

Perceptible cues are often equated with “objects”. However, it is often difficult to determine what an “object” is for a particular space. In many cases such as the example of a Naval exercise, object identification is trivial; ships and aircraft. However, in the case of a building interior, it is not so clear-cut. Fortunately, in those cases where object identification is difficult, visual stimuli can be used. For example, a building interior with no visual detail (e.g. no pictures on the walls, no texture on any surface, etc.) might be classified as sparse to an interior designer and dense to an architect.

Scale

The next spatial characteristic we will discuss (and the one most crucial to this research) is scale. As described earlier, a large-scale environment is defined by (Kuipers, 1978) as

> a space whose structure cannot be observed from a single viewpoint.

By this definition, an environment is either small or large-scale. Unlike many of the other spatial characteristics, this is not a continuum. It is important to describe both the scale of the observer and the scale of the environment before making a classification. A city plaza might be considered small-scale to a typical observer. The viewer can see everything within the complex. However, if the observer is scaled-down to the size of an insect, the same space must be re-classified as large-scale. The observer can no longer see the entire plaza at once. Alternatively, if the observer were enlarged to a size comparable to a large building, the entire city may be considered small-scale. In this same vein, if we now extend the world to include the entire county, the environment is again large-scale.

A space of infinite extent also would be classified as large-scale. As a discrete, close space enlarges, it will tend toward being classified as large-scale. The same is true for spaces requiring only coarse visual detail. As the visual detail demands are raised, the space again tends toward large-scale.

Dimension

Dimension is another spatial characteristic which relates to scale. Similarly to scale, it is not a continuum. A space can be categorized as planar or volumetric. Although both classifications are actually volumes, a planar space is predominantly two-dimensional while a volumetric space makes greater use of the third dimension. A volumetric space may be considered to be a number of stacked planar spaces.

As an example, a walkthrough application where the virtual world and the operator's virtual movement are confined to a plane would be considered planar. If the world were more three-dimensional allowing the operator to control altitude (e.g. to fly), the space would be considered volumetric. The classification is based on the relative extents of each dimension of movement.

Distribution

The density of a space may not be constant throughout. A world with constant density is considered uniform while those without exhibit clustering. In other words, a clustered world may be sparse in some areas and dense in others. The density of objects in most buildings can be considered uniformly distributed. In contrast, a Naval exercise may include a number of battle groups (e.g. ship convoys) which cluster in an otherwise sparse environment.

Activity

The objects to which we have been referring in the previous sections may move. The ships and aircraft in a Naval simulation can be expected to move while the walls and surfaces of a building will not. An object that moves in any way, translation, rotation, or scale, is considered dynamic. This can be extended to consider other attributes as well. For a particular application, a change in color might be considered a dynamic quality. Any object which does not exhibit a change over time is considered static.

Furthermore, the dynamics of an object can be either deterministic or non-deterministic in nature. In the physical world, the movement of a person or vehicle is non-deterministic. However, that same movement in a computer-generated simulation may be deterministic.

Accessibility

ACCESSIBILITY

Restricted ⟷ Free

Accessibility has to do with the physical availability of the space. The physical world is always restricted in some way. We cannot walk through walls or buildings to take a short-cut to some location. When in an open space, we are constrained by physics; gravity, friction, the Earth's surface.

However, in virtual worlds, this may not be true. Simply because the observer cannot see from A to B does not necessarily imply that there is not a direct path from A to B. The virtual world may allow the operator to pass directly through what we would typically consider a solid surface. A world which does not constrain movement is considered free; others are restricted to some extent. Note that restricted accessibility is related to density. It is the density of objects that restricts movement.

Occlusion

OCCLUSION

Obstructed ⟷ Clear

Occlusion can be thought of as visual accessibility. While accessibility asks whether or not the operator can *move* from A to B, occlusion asks whether or not the operator can *see* from A to B. Again, this is directly related to density. There must be something to occlude the operator's view. If the view is occluded, it is considered obstructed. If it is not, it is considered clear.

Note that within the context of virtual worlds, while accessibility and occlusion are very closely related, one does not imply the other. A visually obstructed space may still be freely accessible. The reverse is unlikely, however possible. A space that is visually clear is probably freely accessible as well.

Organization

Lastly, organization has to do with how objects in the space are placed or where they might move. This category is left for last because often, the previous nine dimensions are dictated by the application. The one factor under the most control by the world designer is organization.

A space which has absolutely no structure at all is considered amorphous. A three-dimensional scatter plot may be amorphous in cases where the input parameters show no clear relationship. Alternatively, a highly organized space is considered schematized. Such a space would have an underlying organizational principle exhibiting many of the characteristics described by Lynch and Passini. Most spaces exhibit neither a total lack of organization nor highly developed organization. These spaces are referred to as structured; the average case in physical spaces.

Example Classifications

To further clarify this classification scheme, this section shows a number of examples. Each illustrates a different combination of spatial characteristics. While all of the characteristics described here have only two or three possible values, assignment of a value within a continuum in any particular case may be somewhat subjective. For example, the distribution of objects in a city is considered uniform. Of course this is not strictly true since there are usually numerous parks and other pockets of sparsity. But we make a generalization with regard to the context of the classification; that of wayfinding tasks. In fact, in many cases, the tasks themselves determine the assigned value. For example, to the typical pedestrian (2-D), Chicago is planar. However, it might be considered volumetric to a window washer (3-D) on the Sears Tower.

The Silicon Graphics Performer™ Town demonstration (See Figure5-4) shows a large-scale, planar environment where movement is restricted and the view is typically obstructed. The town is only one part of the environment causing a clustering effect with the outer regions being sparsely populated.

Figure 5-4 Silicon Graphics Performer™ Town

An architectural walkthrough, as shown in Figure 5-5, is an example of a large-scale, dense environment of uniform distribution. However, the extent of the model is relatively close. Movement is obstructed and the view is occluded by the interior walls. The visual stimuli are basically indistinguishable as there is no surface detail present.

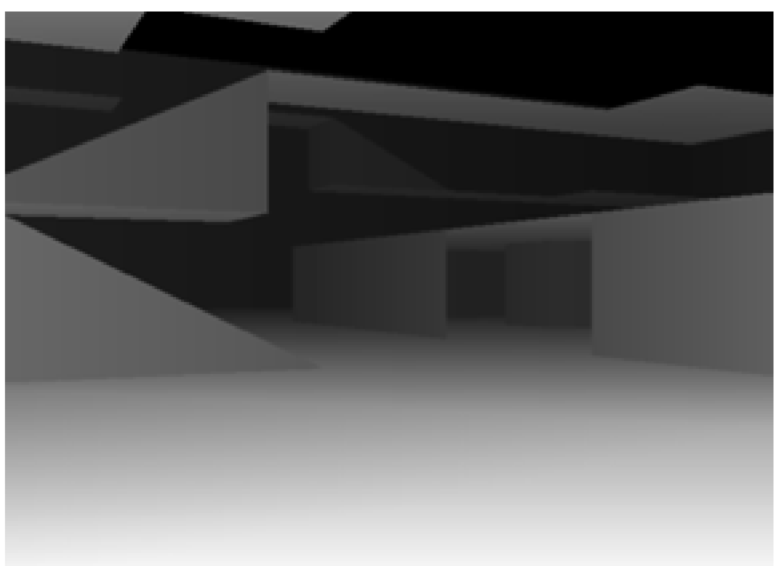

Figure 5-5 A simple architectural walkthrough

A Naval simulation or exercise usually takes place in open sea where the focus of interest is on small groups of ships or aircraft (See Figure5-6). The environment is extremely large and planar but is sparsely populated with clusters of objects. The objects are dynamic and move freely. Accordingly, the view is clear.

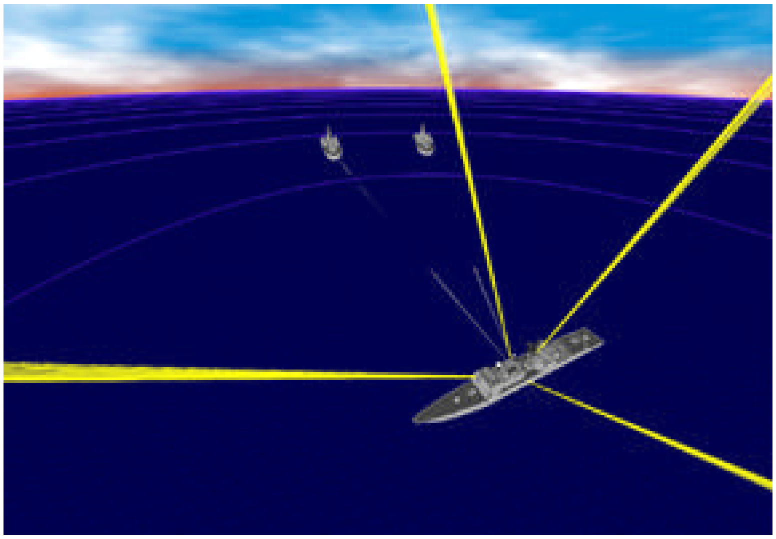

Figure 5-6 A Naval simulation

The Virtual Windtunnel (See Figure 5-7) is an example of a small-scale, planar world with a single focus of attention. The view is obstructed but movement is free allowing the user to move anywhere in the environment. The organization of the world is considered schematized since there is absolute structure imposed on object placement.

The last example is that of a space simulation involving the docking of the space shuttle to a space station (See Figure 5-8). This environment is very large and volumetric. It is sparsely populated with only a few possible foci of attention, usually in clusters. The environment is dynamic, the view is clear and movement is free. The structure of the world is amorphous since little or no structure is imposed on it.

The spatial characteristics of each of these examples are shown in Table 5-2.A visualization across characteristics is possible by stacking the variables vertically and drawing a line connecting the relative values. This has been done in Figure 5-9 on page 100 for the Naval simulation example which is described in more detail in the next chapter.

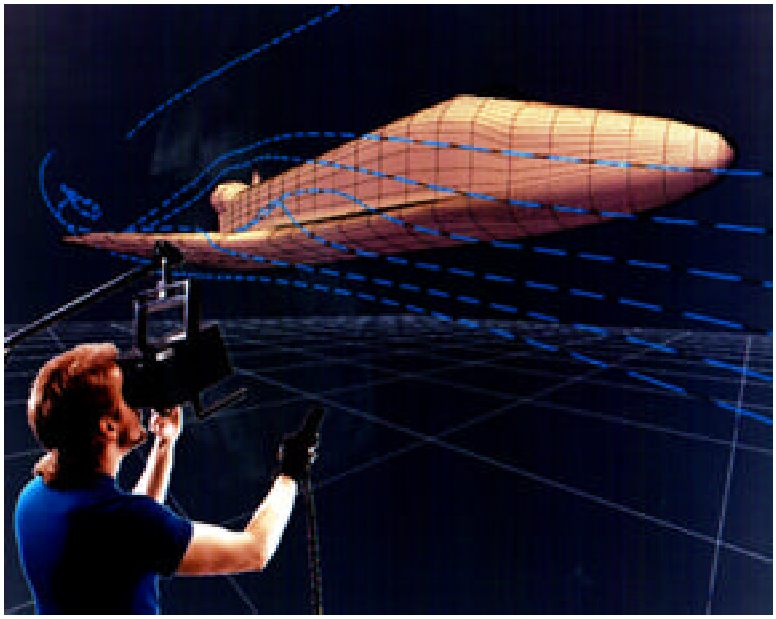

Figure 5-7 The Virtual Windtunnel

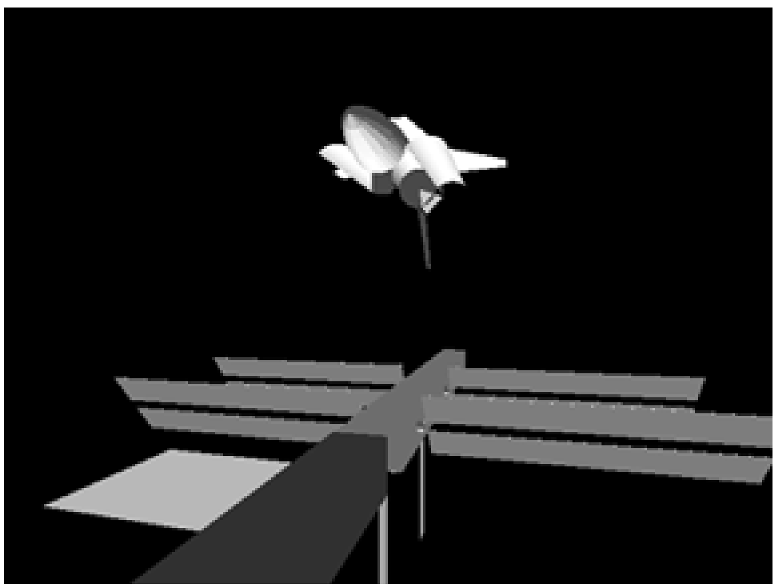

Figure 5-8 A space simulation

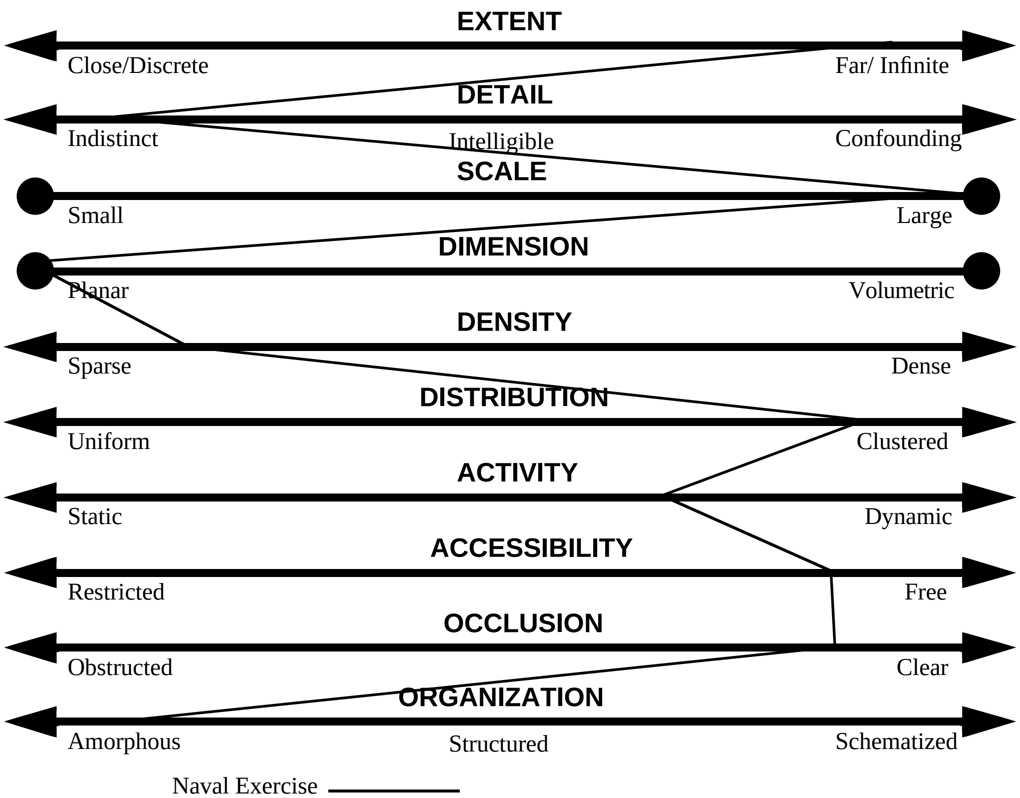

Figure 5-9 The classification categories of spatial characteristics.

Example	Performer Town	A Naval Exercise	The Virtual Windtunnel	A Building Walkthrough	A Space Simulation	Time Square	The Pentagon
Scale	Large	Large	Small	Large	Large	Small	Large
Dimension	Planar	Planar	Planar	Planar	Volumetric	Planar	Planar
Density	Dense	Sparse	Dense	Dense	Sparse	Dense	Dense
Distribution	Clustered	Clustered	Uniform	Uniform	Clustered	Uniform	Uniform
Activity	Static	Dynamic	Static	Static	Dynamic	Static	Static
Occlusion	Obstructed	Clear	Obstructed	Obstructed	Clear	Obstructed	Obstructed
Accessibility	Restricted	Free	Free	Restricted	Free	Restricted	Restricted
Extent	Far	Far	Close	Close	Far	Close	Far
Detail	Intelligible	Indistinct	Intelligible	Indistinct	Intelligible	Confounding	Intelligible
Organization	Structured	Amorphous	Schematized	Structured	Amorphous	Structured	Structured

Table 5-2 Example classifications